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This is an accepted version of a paper published in *Applied Energy*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the published paper:

Thorin, E., Lindmark, J., Nordlander, E., Odlare, M., Dahlquist, E. et al. (2012)

"Performance optimization of the Växtkraft biogas production plant"

Applied Energy, 97: 503-508

URL: <http://dx.doi.org/10.1016/j.apenergy.2012.03.007>

Access to the published version may require subscription.

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Performance Optimization of the Växtkraft Biogas Production Plant

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Abstract

All over the world there is a strong interest and also potential for biogas production from organic residues as well as from different crops. However, to be commercially competitive with other types of fuels, efficiency improvements of the biogas production process are needed. In this paper, results of improvements studies done on a full scale co-digestion plant are presented

In the plant organic wastes from households and restaurants are mixed and digested with crops from graze land. The areas for improvements of the plant addressed are treatment of the feed material to enhance the digestion rate, limitation of the ballast of organics in the water stream recirculated in the process, and use of the biogas plant residues at farms. Results from previous studies on pre-treatment and membrane filtration of recirculated process water are combined for estimation of the total improvement potential. Further, the possibility to use neural networks to predict biogas production using historical data from the full-scale biogas plant was investigated. Results from investigation of using the process residues as fertilizer are also presented.

The results indicates a potential to increase the biogas yield from the process with up to over 30 % with pre-treatment of the feed and including membrane filtration in the process. Neural networks have the potential to be used for prediction of biogas production. Further, it is shown that the residues from biogas production can be used as fertilizers but that the emission of N₂O from the fertilised soil is dependent on the soil type and spreading technology.

Keywords

biogas, optimization, waste, household, fertilizer, N₂O emissions

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Introduction

Most research on the biogas production process has concerned sludge from municipal waste water treatment plants or residues from livestock farms as the substrate. However, the interest to produce biogas from any kind of organic residue as well as from different crops, farm land residues or ley crop has increased. Today the technology for biogas production is not optimized and to be fully commercially competitive with other types of fuels improvements have to be done.

The studies presented in this paper relate to the full-scale biogas plant Våxtkraft in Västerås, Sweden. This plant was taken into operation in 2005; its main parts can be seen in Figure 1. The materials used for biogas production are organic wastes from households and restaurants (also called biowaste) and ley crops silage. The incoming biowaste is mixed with recirculated process water to produce slurry that can be pumped throughout the plant. The solid and liquid wastes are co-digested in a 4000 m³ digestion tank. The biogas produced is subsequently cleaned and purified and used by buses, refuse collection vehicles or cars. The residues from the plant are sent to local farmers as fertilizer [1, 2].

In this paper possible performance improvements of the full-scale biogas plant and surrounding system are studied. The studies are included in the project BioGasOpt, Performance optimization of the Våxtkraft biogas production plant and surrounding system and is performed in cooperation between Mälardalen University, the biogas plant Svensk Våxtkraft AB, the membrane filtration company Mercatus Engineering AB, and the farm Nibble Lantbruk AB. The areas for optimizing the performance of a biogas plant addressed are: treating the feed material in different ways to enhance the digestion rate, limiting the ballast of dry matter in the centrifuge decantate that is recirculated to the reactor, and using the biogas plant residue in the best possible way on farms. Results from previous studies on pre-treatment and membrane filtration of recirculated process water are combined for estimation of the total improvement

Figure 1: The biogas plant Våxtkraft. Used with permission. [1]

potential of these measures. Concerning how the residues can best be used on farmland, laboratory and field studies on the emission of N₂O have been done. Further, the possibility to use neural networks to predict biogas production using historical data from the full-scale biogas plant has been investigated.

The biogas production can be increased by enhancing the digestion rate with a pre-treatment step. The idea is to make the material more accessible to the micro organisms involved in the process. The main feedstock at the Våxtkraft biogas plant is biowaste (about 60 %) and ley crop silage (about 20 %). Studies on the biogas potential of these two substrates show that both the total methane potential and the production rate during the first days of the digestion is much lower for the ley crop silage than for the biowaste (about 20-40 % lower total methane production per mass of substrate for the ley crop silage in total methane production and about 50-70 % lower methane production after 10 days digestion) [3, 4]. Therefore pre-treatment of the ley crop silage to increase the digestion rate is of interest to improve the performance of the plant. Mechanical pre-treatment and pre-treatment by electroporation of ley crop silage has previously been studied by the authors [5, 6]. In the mechanical pre-treatment tests two commercial available grinding machines for recovering of fibres from recycled paper were used, GLD 360 HW and KD 450 from Cellwood Machinery AB. The test was done at Cellwoods industrial scale pilot plant in Nässjö, Sweden. In the electroporation pre-treatment test a lab-scale instrument (from KEA-TEC GmbH) at Luleå Technical University for batch-wise experiments of volumes up to 1 dm³ and with field strength of up to 40 kV/cm and 10 Hz was used. The pre-treatment tests on ley crop silage were made in a 0.1 dm³ container with sample sizes of 0.065 and 0.1 dm³. The performance of the pre-treatment methods has been evaluated with biochemical methane potential (BMP) tests, based on the method described by Hansen et al [7], in both studies. Also the energy efficiency, measured as the energy input needed for the pre-treatment in relation to the increase in energy output in the form of increased biogas yield of the treatments, has been calculated in both studies. Some of the results of the studies are summarised in Table 1. The possible increase in biogas yield by pre-treatment is dependent on both the material to be treated and the pre-treatment method used. Several studies can be found that show that reduction in particle size by physical or mechanical pre-treatment give an increased methane yield, for example [8-11]. However, Hartmann et al [12] state that the fibre size cannot be directly correlated to an increased biogas yield and that there can also be a shearing effect from the treatment that cannot be measured from fibre size alone. Pre-treatment with electroporation has not yet been extensively studied but there are some reports on its positive effect on the biogas production from sewage sludge and source-sorted municipal organic solid waste [13-15].

Another possibility to increase the biogas production is to increase the capacity of the plant by allowing an increased input of new material. In the Våxtkraft biogas plant, the decantate from centrifugation of already digested material is partly recirculated in the process, and the problem

Table 1: Results from previous studies on pre-treatment of ley crop silage [5, 6]

Pre-treatment method	Sample VS [ton/ton ley crop silage]	Total accumulated biogas production (Nm ³ /ton VS)	Methane content	Wh produced/Wh electric energy used	Wh produced/Wh to produce the electric energy used (η=40%)
Mechanical ¹	0.29	235-255 (untreated 151)	50 %	2.2-21	0.9-8.4
Electroporation ¹	0.46	91-469 (untreated 290)	50 %	0.9-3.4 ²	0.3-1.3 ²

¹ Based on methane potential values obtained after 36 days of incubation.

² Only calculated for the cases showing higher gas production than the control

is that the content of dry matter in the recirculated process water is increasing and is today around 4 %. By removing the content of dry matter in the water, the ballast will be reduced and the capacity of the digester can be increased significantly. A possibility to decrease the dry matter of the recirculated process water could be to include a membrane filtration unit, and thereby optimize the plant performance. This has been investigated in a previous study by the authors [16]. Experiments were carried out in a pilot plant built by Mercatus Engineering AB with a ceramic ultra-filtration (UF) membrane unit (Atech Innovations GmbH, 37 channels (diameter=3.8 mm, length=1200 mm), area=0.53 m², pore size = 50 nm, molecular weight cut off = 300 kD, cross flow filtration). The pilot plant was placed at the Växtkraft biogas plant and process water from the process was used in the experiments. Three different operation temperatures (70, 90, 110 °C) were tested. The results from the pilot plant experiments were then used to evaluate the possible increase in biogas production due to increased input of new material to the plant and it was also compared to the energy use of the membrane filtration step. Different plant configurations with different flow rates of process water (10, 20, 26 and 32 m³h⁻¹) passing the membrane filtration step were included in the evaluation. The highest flow rate corresponds to filtration of all the process water recirculated in the plant today while the other cases represent treatment of part of the recirculated flow. Some of the results of the study are shown in Table 2. In other studies on membrane filtration in connection with anaerobic digestion processes (for example [17-21]), the process performance is measured as the ability to clean waste water, while the focus in [16] instead is the ability to increase biogas production. The influence of temperature on the permeate flux is studied as well. Higher temperature decreases the viscosity of the fluid, which leads to a higher permeate flow and provides the possibility to treat large quantities in smaller installations than with normal operation temperatures. An important aspect included in [16] is the energy use in the membrane filtration process compared to the improved output of biogas gained by including the membrane unit.

By modelling the biogas production process the biogas yield could be improved by better possibilities for control of the operation of the plant. A modelling approach based on using empirical data from the process is neural network modelling that has been used for prediction of biogas production [22, 23]. Here some results from using neural network for modelling the biogas production using data from several years of operation of the full-scale Växtkraft biogas plant are presented.

An important part of the performance of the biogas plant is the possibility for a sustainable use of the residues. To use biogas residues on farm land has a number of beneficial effects, such as supplying the soil with nutrients and organic carbon. In a study done by Odlare et al [24] it is shown that the biogas residue can provide the necessary plant nutrients and has the ability to produce nearly 88 % of the crop yield compared to mineral fertilizer. However, to be able to recommend biogas residues as an ecological sound fertilizer it is also important to investigate its impact on the emission of N₂O, since this gas has considerable effects on the stratospheric ozone layer and the global warming [25]. In the soil N₂O is mainly produced by microbial processes as a by-product of nitrification and an intermediate product of denitrification and soil is also known to be a major source of N₂O emissions [26, 27]. The risk for N₂O emissions is

Table 2: Results from investigation of membrane filtration of process water [16].

DM= dry matter				
DM content before filtration [%]	DM content after filtration [%]	Increase in plant capacity, feed of biowaste [%]	Increase in plant methane production [kW]	Power demand¹ for membrane filtration [kW]
3.9-4.4	1.5-1.7	14-29	212 (worst case) 429 (best case)	389 (worst case) 1824 (best case)

¹The power demand calculations assume recovery of heat from the membrane filtration unit with heat exchangers.

high after fertilization and in particular after application of fertilizers containing nitrogen and/or easy available carbon such as mineral fertilizer, pig slurry or biogas residue, which has been shown in several studies [28-30]. In this study both laboratory and field experiments have been performed with the aim to estimate the emission of N₂O from the soil when using residues from the Våxtkraft biogas plant as fertilizer.

Method and materials

In this paper the overall possibilities for improvements of the performance of a full-scale biogas plant is calculated and discussed based on combination of the results from previous studies by the authors concerning pre-treatment of the feed and membrane filtration of the recirculated process water. The use of the biogas plant residues as fertilizer is also investigated in laboratory and field studies as well as the possibility to predict the biogas production with neural network models. The full-scale plant studied is the Våxtkraft biogas plant.

POTENTIAL FOR BIOGAS PLANT PERFORMANCE IMPROVEMENTS BY PRE-TREATMENT AND MEMBRANE FILTRATION

The results from the previous studies by the authors on pre-treatment and membrane filtration of the process water [5, 6, 16] presented in Table 1 and 2 were used to estimate what it would mean for the full-scale biogas plant if these measures are taken. The results of the studies were also converted to the same form to be able to compare them. The parameters compared were the increase in plant methane production and the energy efficiency expressed as the relation of the energy of the extra gas produced to the energy input needed to produce this extra amount of gas. When the energy input is electrical energy also the relation to the corresponding energy to produce the needed electrical energy is calculated.

As a base case the capacity of the Våxtkraft biogas plant to digest 70 tons of biowaste and 15 tons of ley crops per day with a theoretical methane yield of 82 Nm³ methane/ton biowaste and 63 Nm³ methane/ton ley crop silage [4] have been used.

The calculation of the increase in plant methane production ($I_{m,pre}$) due to pre-treatment of the ley crop silage can be made by Equation 1.

$$I_{m,pre} = \frac{(BP_{treat} - BP_{untreat}) \cdot VS_{ley\ crop} \cdot 0.50 \cdot M_{ley\ crop}}{(MY_{ley\ crop\ base} \cdot M_{ley\ crop} + MY_{biowaste\ base} \cdot M_{biowaste})} \quad \text{Equation 1}$$

BP_{treat} [Nm³/ton VS] is measured biogas potential for the treated ley crop silage (from Table 1), $BP_{untreat}$ [Nm³/ton VS] is the measured biogas potential for the untreated ley crop silage used in the experiments (from Table 1), $VS_{ley\ crop}$ [ton/ton ley crop silage] is the fraction of volatile solids in the ley crop silage used in the experiments (from Table 1), $M_{ley\ crop}$ is the plant capacity for ley crop silage per day, $MY_{ley\ crop\ base}$ is the base case methane yield for ley crop silage, $MY_{biowaste\ base}$ is the base case methane yield for biowaste and $M_{biowaste}$ is the plant capacity for biowaste.

The increase of plant methane production ($I_{m,mem}$) due to increased feed of biowaste when membrane filtration is used can be calculated with Equation 2.

$$I_{m,mem} = \frac{\frac{C_{increase}}{100} \cdot M_{biowaste} \cdot MY_{biowaste\ base}}{(MY_{ley\ crop\ base} \cdot M_{ley\ crop} + MY_{biowaste\ base} \cdot M_{biowaste})} \quad \text{Equation 2}$$

$C_{increase}$ [%] is the capacity increase in feed of biowaste (from Table 2). The energy efficiency values are found in Table 1 for the pre-treatment cases and calculated by division of the values for increase in plant methane production and power demand in Table 2 for the membrane filtration case.

PREDICITON OF BIOGAS PRODUCTION WITH NEURAL NETWORK

The data from the Växtkraft biogas plant used for the neural network modeling were results from weekly measurements (with some minor exceptions) made of volatile fatty acids (VFA), total solids (TS), ash content of TS, pH, alkalinity and amount of ammonium in the digester and results from daily measurements of amount biogas produced, methane fraction of the biogas and amount of substrate feed to the digester as well as digester temperature. 110 data points from almost three years of operation were used for this study. 60 data points were used for training the network and they were randomly chosen from the complete set. The remaining 50 data points were used for validation of the neural network. To give the parameters similar initial influence in the network, each parameter was weighted to a value between 0 and 1. The output of the neural networks was how much biogas that will be produced in the coming week.

Three different neural networks were made all with one output node. The first two tested neural networks were simple Adaptive Linear Neuron (ADALINE) networks, one with 8 input nodes and the other with 4 input nodes. The third network was a multi-layer feed-forward neural network with 8 input nodes and a hidden layer with 8 nodes. The input parameters for the 4 node ADALINE network were chosen by selecting the input parameters that had the highest weight on the output node in the 8 node ADALINE network (pH, amount of ammonia, amount of substrate feed to the digester and digester temperature). Feed-forward neural networks are networks in which information only goes in one direction (from input nodes to output nodes), no loops or memory functions are included. ADALINE network is a single-layer feed-forward neural network. Multilayer neural networks are neural networks that contain layers in addition to input and output layers, these layers are called hidden layers. The program used for the neural network modeling was Encog v.2.3.1 which is a neural network and bot programming library. All three networks were trained using resilient propagation training [31] for about 50 000 iterations after which the error improvement was negligible (zero or less than $1 \cdot 10^{-6}$).

USING BIOGAS RESIDUES AS FERTILIZER

The emissions of N_2O from using biogas plant residues as fertilizers was evaluated both in lab-scale and field experiments. In the lab-scale experiment biogas residues from the Växtkraft plant and residues from the membrane filtration tests were amended to two types of soil: one clay soil (CS) and one organic soil (OS). The experiment was designed as a laboratory incubation experiment in 1 dm³ flasks where the gas emissions were measured after 24 hours and 7 days. The field experiment was performed on an organic soil and biogas residues from the Växtkraft plant was spread by two different spreading techniques in growing crop. The first spreading technique (spreader) is conventional spreading with tractor and a tank with the residues while the other technique (distributor) is a new technique where the tractor is driving in the same wheel tracks and spreading two thirds of the fertilizer going in one direction and one third going in the opposite direction. N_2O emissions were measured at 1, 2, 4 and 7 days after residue amendment using field equipment with frames and chambers.

Results and discussion

POTENTIAL FOR BIOGAS PLANT PERFORMANCE IMPROVEMENTS BY PRE-TREATMENT AND MEMBRANE FILTRATION

Table 3 shows the results of the calculations using Equation 1 and 2, and Table 1 and 2. Some values have also been transferred from Table 1 for the comparison of the different measures.

Table 3: Potential for biogas plant performance improvements including pre-treatment and membrane filtration of recirculated process water.

Measure	Increase in plant methane production, I_m [%]	Energy efficiency
Mechanical pre-treatment of ley crop	2.7- 3.4	gas energy/electric energy used = 2.2-21 gas energy/energy to produce the electric energy used ($\eta=40\%$)= 0.9-8.4
Electroporation pre-treatment of ley crop	0-9.2 ¹	gas energy/electric energy used = 0.9-3.4 ² gas energy/energy to produce the electric energy used ($\eta=40\%$)= 0.3-1.3 ²
Membrane filtration of process water ³	12-25	gas energy/energy used = 1.8-4.3 gas energy/energy to produce the electric energy used ($\eta=40\%$) ¹ = 0.7-1.7

¹Negative results have not been included.

²Only calculated for the cases showing higher gas production than the control

³Here it has been assumed that all used energy is electricity but since the energy demand is partly a heat demand also other energy sources is possible.

The results of the studies indicates that a combination of ley crop pre-treatment and increased capacity for biowaste due to membrane filtration has the potential to increase the methane production of the biogas plant with up to over 30%. It is important to point out that the evaluations of the effects of the pre-treatments have been performed in batch tests and can therefore not fully be used to predict the increased yields in a full scale plant where also the retention time and mixing is of importance. The electroporation instrument tested is also in lab scale and the performance in full scale equipment remains to be investigated. Due to small reaction chambers the material was shredded before the pre- treatment with electroporation. Shredding of the ley crop is also a kind of mechanical pre-treatment even though not to that small particle sizes as with the equipment tested in the mechanical pre-treatment study. Maybe a combination of mechanical pre- treatment and electroporation could be of interest to increase the gas yield even more than one single pre-treatment method. The substrates used in the Växtkraft biogas plant are heterogeneous materials and their properties can also vary over time and with this the methane potential and the possible gas yields. This was also a problem in the studies of the pre-treatment of ley crop since the control samples showed large standard deviations.

Concerning the energy efficiency of the measures investigated the pre-treatments and membrane filtration of the process water show the possibility to give positive energy balances, and the mechanical pre- treatment is the most energy efficient measure.

PREDICITON OF BIOGAS PRODUCTION WITH NEURAL NETWORK

Figure 2 shows the results of the neural network modelling of the biogas production at the Växtkraft biogas plant. The average error of the predictions with the models is 16-19%, with a minimum error of 0.1 -0.2 % and a maximum error of 180-286 %. The standard deviation divided by the average real biogas production is 17-20 %.

Figure 2: The graph shows the results of the neural network modelling of the biogas production at the Våxtkraft biogas plant.

Given the simplicity of the neural networks chosen and the available data the results are reasonably good for at least the two ADALINE networks that follow the general trend of the biogas production with some accuracy. It can be noted that the difference between using only 4 nodes instead of 8 nodes for the ADALINE network is small and therefore the four chosen input parameters are probably of more importance to the biogas outcome than the input parameters that were not selected.

The multilayer feed-forward network with one hidden layer does not show higher accuracy. The network rather shows greater deviation from the amount biogas actually produced. Maybe the network becomes sub-optimized because the data set is not large enough. It might be possible that a neural network trained with a larger training set and where input parameters are measured continuously could predict the biogas production better. It is also possible that other types of more advanced neural networks would be more suitable for the task.

USING BIOGAS RESIDUES AS FERTILIZER

The results of the experiments on N_2O emissions from biogas residues in the lab-scale experiments showed that 24 hours after application of biogas residue the organic soil produced significantly higher emission rates than the clay soil (see Figure 3). This was expected since the organic soils contain high amounts of organic material and high microbial activity. The filtered biogas residue shows slightly higher emission rates of N_2O , however, this difference was not statistically significant due to large variations between the replicates.

The results from the field experiment showed that using the distributor instead of the spreader decreased the emissions of N_2O (Figure 4), although this difference was only statistically significant at day 4 and day 7. Furthermore, after using the distributor, the emission continued to stay low later in the experiment, which can be compared with areas where the spreader was used where the emissions increased for each sampling day with the highest emissions at day 7. N_2O emission from the soil is often caused by “hot spots” where anaerobic conditions occur. The distributor probably spread the residue more evenly at the soil particles, causing fewer anaerobic hot spots in the field, and hence led to lower emissions of N_2O .

Figure 3: Emissions of N₂O measured from a clay soil (CS) and an organic soil (OS) after application of biogas residue (BR), filtered biogas residue (BRMF) and control with no application. Grey bars show emissions after 24 h and black bars after 7 days. Statistically significant difference ($p=0.05$) between treatments is indicated by different letters.

Figure 4: Emissions of N₂O measured from an agricultural field after application of biogas residue at 1, 2, 4 and 7 days. Black, dark and light grey bars represent the spreader, the distributor and the control, respectively. Statistically significant difference ($p=0.05$) between treatments is indicated by different letters.

Conclusions

The conclusions concerning performance optimization of the full scale Våxtkraft biogas production plant can be summarized as:

- Pre-treatment of the ley crop substrate mechanically or with electroporation and using membrane filtration to treat the process water for recirculation of process water all has the potential to increase the biogas plant performance.
- Of the studied measures the mechanical pre- treatment of the ley crop shows the highest energy efficiency.

- Neural networks have the potential to be used for prediction of biogas production even though the simple networks used in our study could not predict the extreme points but followed the general trend in the production.
- The residues from biogas production can be used as fertilizers in the agriculture but soil type as well as spreading technology should be considered regarding emissions of N₂O.

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Acknowledgements

The Knowledge Foundation is acknowledged for funding the BioGasOpt project.